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MODELLING OF CORROSION PROTECTION FOR REINFORCED CONCRETE STRUCTURES WITH SURFACE COATINGS

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Abstract. Corrosion is a serious problem for the durability of reinforced concrete structures. These structures need to be protected from corrosion in a variety of exposure conditions ranging from atmospheric to continuous immersion in water or chemicals. One of the ways to protect reinforced concrete structures from corrosion is to use protective coatings. The surface barriers of non-degradable materials are able to slow down considerably the rate of deterioration of concrete structures and to overcome most durability problems associated with external attack. Design of durability of concrete structures with protective coatings needs to be established. In this paper a general framework for service life prediction and reliability evaluation of anticorrosion protective system (CPS), which is represented by protective surface barrier, concrete cover, and steel reinforcement itself of reinforced concrete structures, is presented. This approach is based on a reasonable understanding of the main degradation processes of all components ensuring protection ability and durability of concrete structures. The effect of repair of CPS components on extending the service life of a whole protective system is considered. Numerical example for reliability verification of CPS is also given.

Keywords: reinforced concrete, corrosion, protection system, durability, reliability, service life.

1. Introduction

Deterioration of reinforced concrete structures exposed in man-made or atmospheric aggressive conditions is a common problem in many countries of the world. Frequently, due to corrosion, the resistance of structures decreases much earlier than their expected service life and the need to carry out repairs of degraded structures is increasing exponentially.

The durability of reinforced concrete structures depends both on the resistance of the concrete against physical or chemical attack and on its ability to protect steel bars against corrosion. Many fundamental works have been published on this subject. Several studies have been conducted on modelling the corrosion processes and assessing the effect of corrosion on the performance of concrete structures. The synthesis of investigations on concrete and reinforcement degradation and general guidelines for probabilistic durability design, for instance, is presented in Dura Crete Project (Dura Crete 1998), a consortium of 12 European Union member states. Most available studies have been focused on the corrosion of reinforcement caused by concrete carbonation and chloride attack. The publications on corrosion of reinforced concrete structures are very extensive and will not be discussed here.

Concrete is not chemically resistant and impermeable to gases and fluids. In a number of situations, concrete and embedded steel needs some additional protection against chemical attack which can only be afforded by a barrier resistant to the action of the chemical agents encountered. Several methods have been elaborated for anti-corrosion works such as corrosion-inhibiting admixtures, non-reactive reinforcing bars (stainless steel, non-metallic or epoxy-coated reinforcement), cathodic protection, re-alkalisation, desalination, various protective coatings.

Impermeable barriers, which prevent contact with the external attack, are among anti-corrosion protection methods currently being adopted to reduce the risk of reinforcement corrosion or to protect a whole concrete structure. Methods for improving the performance of reinforced concrete structures by surface treatment or coatings have been investigated for many years (e.g., Almusallam *et al*. 2002, 2003; Chung 2004; Delicchi *et al.* 2004; Камайтис 1992; Kamaitis 2007a, b; McCarty *et al.* 2004; Medeiros, Helene 2008; Raupach, Wolff 2005; Remmele 2003; Rodrigues *et al*. 2000; Schiessl 1994; Seneviratne *et al*. 2000; Vipulanandan, Liu 2005) and many standards are published (ASTM, ACI, JIS, JASS, etc.) (Mays 1999). Generally, Standards and Recommendations specify materials and methods of application and are no more than general guides for choosing the coating for a particular application. Much of the work mentioned above has been carried out on the mechanical properties and durability of polymer-based materials, surface preparation for coatings, coating adhesion to concrete, concrete crack-bridging ability, permeability, and different coating systems evaluation in laboratory or "in situ" conditions. The results of research show that surface

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treatments delay and retard the rate of deterioration and permeability to aggressive substances and can increase the service life of structures when repair is required.

Time-dependent modelling of corrosion in reinforced concrete structures are based mainly on two phases − initiation phase and propagation phase with few sub phases. The latter include formation of cracks and spalling of concrete cover as well as loss of steel crosssection and/or bond between reinforcement and concrete. Over a long period, this may result in structural failure. In case of a coated structure, three levels of protection can be considered: protection barrier, concrete cover and reinforcement itself. Note, that epoxy coatings sometimes are used for protecting steel reinforcement. Fibre reinforced polymer bars provide another option for corrosion protection at the level of reinforcement.

However, there are only limited attempts to provide satisfactory analytical methods to assess the durability of protective measures, as a whole. In general, only the recommendations for selecting protective coatings for exposure environments are presented. The current state of research in resistance deterioration of protected structures remains unsatisfactory and further research on the prediction of service life of reinforced concrete structures with the various protective measures is needed.

In this paper, a concept is introduced and used for considering multi-level anticorrosion protection durability for evaluation and service life prediction of reinforced concrete structures. The approach takes into account the performance of protective surface barrier, concrete cover and steel reinforcement as a whole that can be denoted as corrosion protection system (CPS). Lifetime functions of each component in the system can be used to predict the service lifetime of CPS. The effect of recoating and repair of CPS components on extending the service life of a whole protective system in aggressive environments is also considered.

2. Limit state definition of reinforced concrete structures with protective surface barriers

Design and verification of durability of new or existing reinforced concrete structures are not simple. Corrosion is a stochastic process. Durability of structures is influenced by:

- introduction of new conceptions, materials and construction techniques, requiring repeated trials and errors as well as the tendency to provide the structures at the lowest possible cost;
- very wide variation of exposure conditions during service life, which depend on the situation of a structure and location of an individual member within a structure;
- significant number and rates of deterioration mechanisms and interactions, which result from combinations of the environment, quality, size and configuration of a structure;
- manifestation of the durability problems after a long time when the degradation of the existing structures is well advanced; very often the causes of degradation are obscure, and the construction records or condition survey data are missing;
- different levels of maintenance, that is directly related to the condition state of the structures;
- gross errors during design, execution or operation.

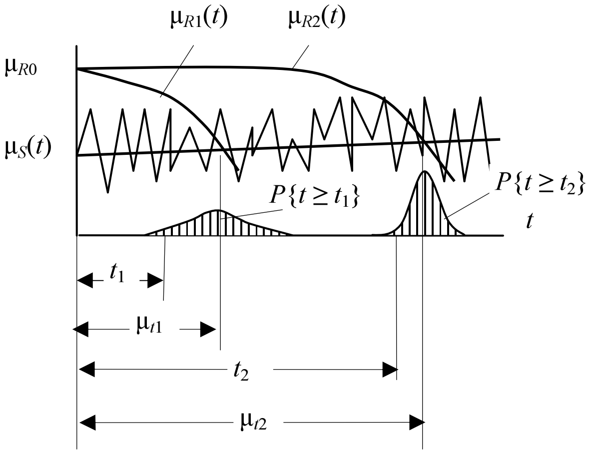

Fig. 1. Effect of surface protective barrier on the service life of concrete structure

Fig. 1 illustrates the life-cycle performance of a typical reinforced concrete component. Once designed and constructed structures undergo gradual degradation in resistance and serviceability. In general, the performance of components decreases with time due to mechanical, physical or chemical process. By using protective barriers, it is possible to reduce the rate of degradation and to extend the service life of structures exposed to aggressive environments. The degree to which CPS will provide the durability of a structure in a given environment is a function of the type of protective barrier, the quality and the depth of concrete cover, and the degree to which the degradation of steel reinforcement is acceptable. Unacceptable level of reinforcement degradation is governed by material (or diameter) and bond between reinforcement and concrete losses.

Generally, according to Codes and Recommendations corrosion of reinforcement is not tolerated. However, the structures with corroding steel are often observed in practice (e.g., Kamaitis 2002). Some typical examples are shown in Fig. 2.

The necessity of protective barrier on a new or existing structure can be based, for example, on the ratio t/t_d, where t and t_d are expected (or observed) and required (or designed) service time of the structure, respectively. If $t/t_d \geq 1$, it is evident, no special protection measures are needed. If $t/t_d = 0,8 - 1$, it is believed, the level of performance can be achieved only by modification of concrete cover and/or structural detailing. If $t/t_d < 0,8$, special protective barriers either to the concrete surface or to the reinforcement to meet the durability requirements should be provided.

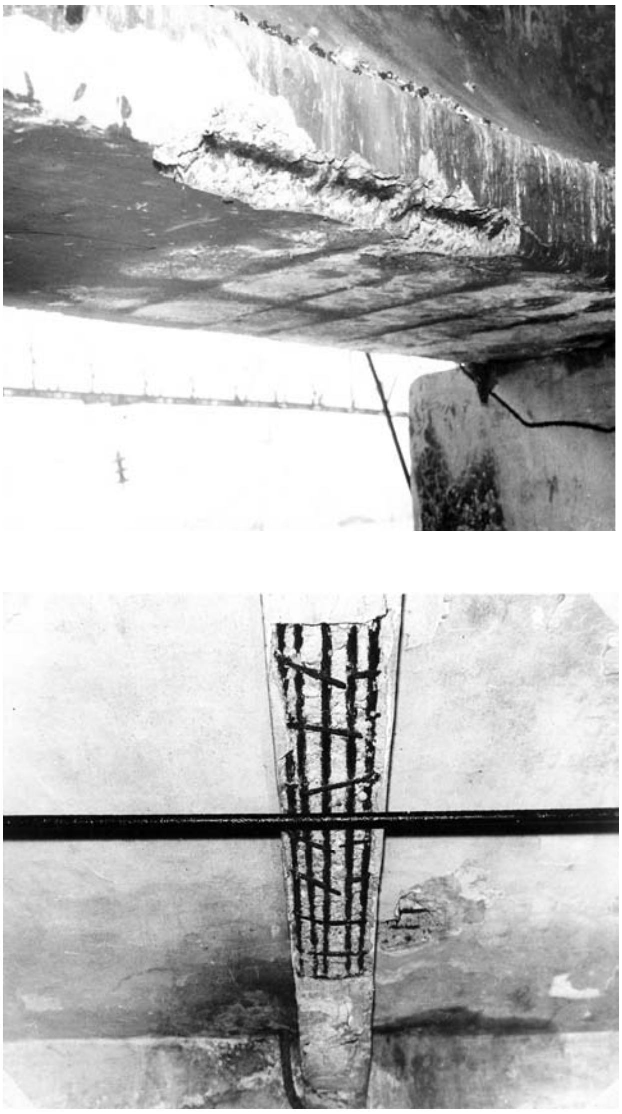

Fig. 2. Bridge reinforced concrete girder (top) and floor beam of industrial building (bottom) in service with corroding reinforcement

The limit states of deteriorating structures are based on the effect of actions, $S(t)$, compared to materials or structural time-variant resistance, $R(t)$. The verification can be performed in resistance or lifetime format:

$$g(t) = R(t) - S(t) = R_0\varphi_R(t)\theta_R - S(t)\theta_S > 0, \quad (1)$$

$$g(t) = t\theta_t - t_d > 0, \text{ for all } 0 < t \le t_d, \quad (2)$$

where $g(t)$ is the margin of safety with $g(t) > 0$ denoting safe and $g(t) \le 0$ denoting failure; R_0 is component capacity in the undegraded (original) state; $\varphi_R(t)$ – degradation function; θ_i – uncertainty of the calculation models and errors in data observation and recording; t – the time of assessment; t_d – the design or target service life.

Reliability of deteriorating structures without and with protective barriers is defined, respectively, as:

$$P\{t \ge t_1\} = P\{g_1(t) > 0\} = P\{R_0\varphi_{R1}(t)\theta_{R1} > S(t)\theta_S\} \ge P_{t\,\mathrm{arg}},$$
$$\text{for all } 0 < t \le t_{d1}, \quad (3)$$

$$P\{t \ge t_2\} = P\{g_2(t) > 0\} = P\{R_0\varphi_{R2}(t) > S(t)\theta_S\} \ge P_{t\,\mathrm{arg}},$$
$$\text{for all } 0 < t \le t_{d2}, \quad (4)$$

where P_{targ} is acceptable level of structural reliability.

The time-dependent monotone decreasing degradation function $\varphi_R(t)$ can be expressed in different forms (linear, parabolic, square root, etc.) with the following boundary conditions:

at $t = t_0$, $\varphi_{R1}(t_0) = \varphi_{R2}(t_0) = 1{,}0$;

at $t = t_d$, $\varphi_{R1}(t_{d1}) = \varphi_{R2}(t_{d2}) = \varphi_{\min}$;

at $t_d > t > t_0$, $\varphi_{R2}(t) > \varphi_{R1}(t_d)$,

where $\varphi_{\min}$ is min acceptable deterioration function.

The greater $\varphi_{R2}(t)$ is, the more reliable structure with prolonged service life can be obtained.

The effectiveness of protective barrier on the durability of reinforced concrete structures can be expressed, for instance, by rapport $\frac{\mu_{t2}}{\mu_{t1}} > 1$ or $\frac{t_2}{t_1} > 1$. The problem is to be able to assess the degradation level and service life t_1 and t_2 for given situations.

Anticorrosion protective measures are costly. Costs of protection may be a significant part of the overall life-cycle costs of a concrete structure. Therefore, the benefits to be gained from special protection should be balanced between required level of reliability and cost. The design of optimum protection system can be based on well-known optimization problem:

$C_{tot} \rightarrow \min$
subject to $P\{t \ge t_d\} \ge P_{t\,\mathrm{arg}}$,

where C_{tot} is total direct and indirect costs including inspections, repair and expected losses due to failure of the structure.

The objective of the optimization process is also to evaluate the different protection scenarios. Many studies have been done to determine optimal maintenance strategies for deteriorating structures. They are reported in numerous publications and are beyond the scope of this paper.

This section illustrates the importance of protective barriers for the extension of service life on RC structures exposed to aggressive environments. It is evident that detailed and realistic investigations in this subject are needed. On the other hand, accurate predictive analysis associated with corrosion protection measures for the development of design procedures is of particular interest.

3. CPS model and assumptions

Fig. 3 represents the service life model of CPS exposed to aggressive agents. It is obvious that the required protection ability of CPS for reinforced concrete is governed by the resistance of all component materials to the agents involved and penetration/diffusion properties of protective barrier and concrete cover. Protective barriers as well as concrete cover and steel in aggressive environments have limited service lives.

The service life of CPS can be divided into 3 stages: service life of protective barrier (t_b), concrete cover (t_c), and the last phase during which an unacceptable loss of reinforcement section has occurred (t_s). Protective barrier is the most important and extremely loaded component of a protective system. After failure of such a barrier the lifetime of CPS is governed by degradation of concrete or penetration of aggressive substrates through the concrete cover and then by the rate of steel bars corrosion. The corrosion of reinforcement relates closely to the deterioration and safety of the structure.

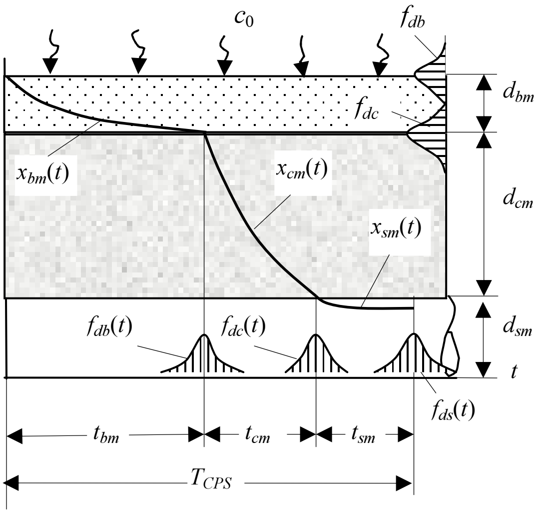

Fig. 3. Service life of CPS

The basic assumptions made to model the durability of CPS are:

a – degradation function of CPS is independent of the load history; only deterioration due to an external aggressive attack is considered;
b – the system consists of three non-identical components, i.e. protective barrier, concrete cover and reinforcement; all components are activated continuously upon failure of an operative component;
c – shape and rate of the degradation functions for protective barrier, concrete cover, and reinforcement are specific and must be known;
d – all components of system are repairable; the repaired components are restored to an as-good-as-new condition (to initial performance level), each time repair is applied;
e – failure of CPS is the result of failure of all components making up the CPS.

Based on these assumptions, a model representing service life of CPS was chosen and is shown in Fig. 3. This model presents the protection ability as a function of time. The CPS is composed of three components, each having different performance curves with several alternative rehabilitation strategies. In general case, we assume that reinforcement is also repairable.

4. Service life formulation of CPS

The service life of CPS can be expressed by Eq. (Fig. 3):

$$T_{CPS} = (t_{bm} + t_{cm})\upsilon_t + t_{sm}, \qquad (5)$$

where t_{bm} is service time of protective barrier as a function of type and thickness of cover; t_{cm} – time for concrete deterioration as a function of concrete cover quality and thickness; t_{sm} – time for reinforcing bars to cause acceptable corrosion level as a function of environment conditions, type of structure and reinforcement. It is obvious that t_{bm}, t_{cm}, and t_{sm} can be different lengths of time.

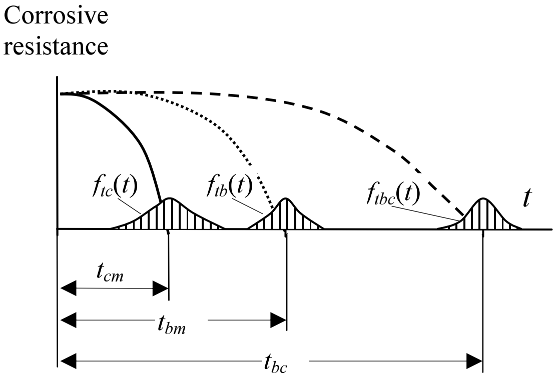

Fig. 4. Corrosive resistance of protective barrier and concrete cover

Quality and thickness of a protective barrier and concrete cover are known to vary spatially over the structure's surface. In practice, the deterioration process also is not uniform and at any time different parts of protection system will be in different states. It is unlikely that deterioration of these components will take place in the same critical sections. Hence, the corrosion resistance of the system composed of protection barrier and concrete cover is not equal to the sum of corrosion resistance of individual components (Fig. 4). Then, a chance that the critical sections in the protective barrier and concrete cover match-up is small and can be evaluated by the parameter

$$\upsilon_t = \frac{actual\ \ value}{predicted\ \ value} = \frac{t_{bc}}{t_{bc.d}} \geq 1{,}0, \qquad (6)$$

where t_{bc} and $t_{bc.d}$ ($= t_{bm} + t_{cm}$) are actual and predicted (design) service time of protective barrier + concrete cover, respectively.

Note also that $t_{bc.d}$ is defined by standard testing procedures and naturally reflects some conservatism.

Components of protection system allow controlling the corrosion rates of structures by periodic recoating or repairing the components over the lifetime of a structure. Taking into consideration the number of recoatings, n_b, repairs of concrete cover, n_c, and that of reinforcement, n_s, during the required service time of structure, t_d, the main design time of protective system can be found as follows:

$$T_{CPS} = \left(\sum_{i=1}^{n_b} t_{bmi} + \sum_{i=1}^{n_c} t_{cmi} \right) \upsilon_{ti} + \sum_{i=1}^{n_s} t_{smi} \ . \qquad (7)$$

The limit state of CPS or its components is defined as

$$g(t) = R_{CPS}(t)\theta_R - S_{cor}(t)\theta_S > 0 \qquad (8)$$

or in life-time format

$$g(t) = \left(\theta_{tb}\sum_{i=1}^{n_b} t_{bmi} + \theta_{tc}\sum_{i=1}^{n_c} t_{cmi}\right)\upsilon_{ti} + \theta_{ts}\sum_{i=1}^{n_s} t_{smi} - t_d > 0. \qquad (9)$$

The variables $S_{cor}(t)$ and $R_{CRS}(t)$ entering the Eqs (8) and (9) can be of any quantities and expressed in any units. In the design or verification of durability of CPS or its components, $S_{cor}(t)$ can be penetration depth $[x(t)]$ or concentration of aggressive agents on the depth x (c_x), extent of barrier cracking or delaminating, concrete cover cracking/spalling or reinforcement corrosion intensity. $R_{CRS}(t)$ is the resistance of a system to corrosive actions or limiting performance criteria which can be interpreted as the actual depth of protective barrier (d_b) or concrete cover (d_c), critical concentration of aggressive agents on concrete or reinforcement surface (c_{cr}), admissible level of barrier delaminating or concrete cracking/spalling, loss of rebar diameter.

It is evident that aggressive environmental service actions as well as physical and geometrical parameters of CPS components are random variables. Hence, to preserve serviceability and safety of protection a reliability analysis is indispensable.

In the probability based approach the distribution of T_{CPS} according to Eqs (5) and (7) can be found, if the distributions of the random variables t_{bi}, t_{ci} and t_{si} are known. Statistical parameters should be obtained from laboratory or field experimental data.

In general, the probability distributions of the degradation of building materials and components are close to the normal or lognormal distribution. For instance, if the probability distribution of the time to first failure of CPS components is normal, the normal should be and time to failure distribution of CPS. The service time of CPS and its components in Eqs (5), (6), (7) and (9) are presented in terms of their mean values. Then, the time to the first failure of component *j* is defined as

$$t_j = (1 - \beta_{tj}V_{tj})t_{jm}, \qquad (10)$$

where $\beta_\bullet$ and $V_\bullet$ is safety index and coefficient of variation of •, respectively.

The reliability index of component *j* is defined as

$$P\{t_j \geq t_{dj}\} = P\{R_j(t)\theta_{Rj} > S_{cor.j}(t)\theta_{Sj}\} = \Phi(\beta_{tj}) \geq P_{t\arg.j}. \qquad (11)$$

For the given acceptable probability $P_{targ.j}$, the time to the first failure t_j of component *j* can be determined.

That the protection system will work for the prescribed period of time, t_d, the following expression should be verified

$$P\{T_{CPS} \geq t_d\} = P\{\Sigma t_j \geq t_d\} = \Phi(\beta_T) \geq P_{t\arg}, \qquad (12)$$

where P_{targ} is a target reliability indice, which is based on the failure consequences of protection system.

According to Eq (6), the parameter υ_t can be determined:

$$\upsilon_t = \frac{t_{bc}}{t_{bc.d}} = \frac{(1-\beta_{tbc}V_{tbc})t_{bc.m}}{(1-\beta_{tb}V_{tb})t_{bm} + (1-\beta_{tc}V_{tc})t_{cm}} \geq 1{,}0. \qquad (13)$$

5. Life cycles of *CPS* components

It is obvious that the shape and rate of degradation functions in Eqs (8) and (9) are specific for protective barrier, concrete cover and reinforcement bars are strongly influenced by nature and quality of structure components as well as exposure conditions, which define the degree of protection required.

Table 1 gives a summary of the effects of some destructive agents on reinforced concrete components and polymer coatings. This information is based on literature sources as well as the author's experience and is only general information to be used as the basis for beginning an investigation. It is obvious that the number of physical and chemical destructive agents which can attack structure components is large and is not the only factor which determines the rate of attack, but also embodies the chemical nature and concentration of the substances, temperature, pressure, as well as their cyclic changes.

Table 1. Physical and chemical effect on corrosion protection components by various agents

Effect	Polymer coatings	Cement concrete	Steel in concrete
Acids	DS	DR	IC
Alkalis	DS	NH	NH
Salt solutions	NH	NH	IC
De-icing salts	NH	scaling	IC
Water	DS	NH	C
Sea water	DS	D	C
Fats, oils, wastes	DS	DS	C
Gases (CO_2, Cl, SO_2, diesel)	DS	DS moist concrete	C
Freezing and thawing	NH	D	NH

NH = not harmful; D = disintegrates; DS = disintegrates slowly; DR = disintegrates rapidly; C = corrosion; IC = intensive corrosion.

It is necessary to note that well-designed concrete structures, made with good quality concrete are relatively impervious to most waters, soils, and atmospheres. Good quality concrete can be made resistant by a proper proportioning, compacting, curing, and use of different admixtures to yield adequate strength and low permeability. Although permeability to liquids and gases may vary considerably among different concretes, even the best concretes have always some degree of permeability. Penetration of gases and fluids into the concrete is frequently accompanied by chemical reactions mainly with cement or by physical actions due to formation of oxides, salts or ice, causing expansion and disintegration of the concrete.

Steel corrosion in reinforced concrete leads to concrete cover cracking/spalling, to a reduction in bond strength and a reduction in bar cross-sections. In practice these degradations are randomly distributed in terms of location and intensity.

Protective barriers such as polymer coatings are also not absolutely resistant to the action of all agents encountered and, in general, also have limited service lives. Various thermoplastic and particularly thermosetting polymers (e.g., epoxies, polyesters, urethanes) are proposed to use as protective coatings. Disintegration of coatings named in the table is specified as degradation by swelling, dissolution, scission or weathering involving also the diffusion phenomena. However, resistance to attack is, in general, much better for polymers than for cement concrete or steel.

Given the complexity of the deterioration of CPS components, we will consider that the rate of corrosion of protective barrier, concrete cover and steel reinforcement may be expressed, for instance, as corrosion rate, λ, that is, the reduction of the mechanical strength due to physical/chemical degradation or permeability/diffusion due to the transfer of destructive agents, even without compositional changes, which can be viewed as a degradation of mechanical properties and cross-section (thickness) losses per unit of time. Corrosion rate is a function of many variables and usually should be determined by mathematical models of the physical transport processes and of empirical data.

The survivor function in Eq. (5) or (7) of polymer protective barrier in aggressive chemical solutions, for instance, can be expressed by an exponential distribution (Kamaitis 2007b):

$$x_b(t) = d_b[1 - a\exp(-\lambda_b t)] \quad \text{for} \quad t_b \geq t > 0, \tag{14}$$

where $x_b(t)$ is attack-penetration depth; d_b – coating thickness at $t = 0$; λ_b – the rate of coating degradation.

In a probability-based approach and normal distribution of variables, the survivor function of protective coating can be expressed as follows:

$$P\{t_b \geq t_{db}\} = P\{d_b \geq x_b(t)\} = \Phi(\beta_{tb}) = \Phi\left\{\frac{d_{bm}\theta_{dm} - x_{bm}\theta_{xm}}{[\sigma^2(d_{bm}\theta_d) + \sigma^2(x_{bm}\theta_x)]^{1/2}}\right\} \geq P_{t\arg.b}, \tag{15}$$

where d_{bm}, x_{bm}, θ_{dm}. and θ_{xm} are the mean values and $\sigma(\bullet)$ is standard deviation of $\bullet$; $P_{targ.b}$ is barrier target reliability.

Design and detailing of concrete cover and reinforcement in the presence of concrete deterioration due to sulphate attack, freeze-thaw cycling, and reactive aggregate reactions as well as reinforcement corrosion caused by concrete carbonation and chloride penetration have been treated by a number of authors and reported in numerous publications. Recently, degradation models for the application of de-icing salts, atmospheric CO_2 or marine exposure have been put forward which include two or three stages of initiation, crack formation and propagation to a defined limit state. In general, the last two components – concrete cover and reinforcement can be designed separately according to numerous recommendations (e.g. Dura Crete 1998). For instance, for atmospheric or chloride induced corrosion (bridges, parking garages) the increase of carbonation or chloride penetration depth, $x_c(t)$, with time leading to depassivation of reinforcement can be predicted using simplified equation:

$$x_c(t) = \lambda_c t^n \quad \text{for } t > t_b \tag{16}$$

or

$$t_c = \sqrt[n]{\frac{d_c}{\lambda_c}}, \tag{17}$$

where λ_c is a constant; d_c – thickness of concrete cover; n – exponent of time.

Similar approach can be used for modelling concrete degradation in liquid aggressive solutions.

Once the passivity of reinforcement has destroyed, some lap of time is needed to cause the concrete cover cracking or spalling. This time can exceed the value of 6 years (Bentz 2003) or can be taken, for example, as $10T_{cr1}$ (Val, Stewart 2003), where T_{cr1} is the time to first concrete cracking. At this stage, the loss of bar diameter generally is very low (e.g. Andrade *et al.* 1993; Allam *et al.* 1994; Maruyama 1999; Almusallam 2001) and it is very unlikely the corrosion will considerably affect the strength of a structure.

When the concrete cover has cracked or spalled, the intensive corrosion of exposed reinforcement is initiated. As a corrosion of steel bars proceeds, the rust layer increases in thickness leading to loss of cross-sectional area and relating closely to the deterioration of a structure (e.g. Jokubaitis 2007). This non-linear phase is controlled by diffusion of oxygen or aggressive substrates through the rust layer. This process can be modelled in a simplified form as

$$x_s(t) = \alpha\lambda_s t_s^n, \quad \text{for } t > t_b + t_c \tag{18}$$

or

$$t_s = \sqrt[n]{\frac{d_{s.adm}}{\alpha\lambda_s}}, \tag{19}$$

where $x_s(t)$ is the depth of steel corrosion; $d_{s.adm}$ – maximum admissible depth of corrosion which depends on the type of structure and that of reinforcement; λ_s – the rate of uniform steel corrosion; α – a coefficient depending on the type of attack: for uniform corrosion $\alpha = 2$, in the case of pitting $\alpha = 4{-}8$. The values of both parameters λ_s and n are influenced by environment and type of reinforcement.

It should be pointed out that it is difficult to decide an acceptable limit for steel reinforcement corrosion. As it was mentioned above, according to Codes and Recommendations, corrosion of reinforcement is not tolerated. Admissible depth of corrosion frequently is expressed as limiting value of reinforcement diameter or area. The cross-sectional area reduction by 25–30% of reinforcement bars seems to be the failure criterion of corrosion-affected reinforced concrete structures (e.g. Amey *et al.* 1998; Gonzales *et al.* 1996; Val, Stewart 2003). In epoxy coated reinforcement the deterioration of epoxy coating can be accepted as a limit state. The admissible depth of reinforcement corrosion is always the matter of discussion.

Similar to protective barrier [see Eq (15)] the probabilistic analysis for concrete cover and reinforcement degradation also can be carried out. It is obvious that suitable examinations are necessary for each deterioration factor to fix the mean values and their dispersions.

Optimal life cycle performance of CPS can be achieved in many ways. Different barrier materials, concrete compositions and reinforcement corrosion criteria as well as repair scenarios including initial and maintenance costs, can be considered to obtain desirable protection abilities for particular applications. This will be not discussed herein due to the limited space of paper.

As far as we know, it is very few investigations, which combine the consequences of protected structure corrosion with SLS or ULS, although a number of studies has been conducted on durability of protective coatings, as it is mentioned above. A classification of structures according to the type of deterioration and consequences of failure should be considered. In a high aggressive environment for important structures, including prestressed concrete structures for which corrosion of steel reinforcement is not allowed, for SLS the delaminating of coating, depassivation of steel in concrete or the concrete cover cracking/spalling can be accepted as the end of service life. A possible approach to modelling the durability of ancillary components is to take into account visible degradation of reinforcement based on safety or appearance requirements of a member. For ULS loss in reinforcement cross-section or bond strength is generally accepted (Coronelli 2002).

6. Illustrative example

To illustrate the application of CPS probabilistic analysis a semi-realistic reinforced concrete storage rectangular tank for industrial inorganic acid water is considered.

Given: sulphuric acid concentration of c_0 = 49 mg per litre and pH ~3. Concrete B35, cement content C = 400 kg/m^3; W/C = 0,42; k_{CaO} ≈ 620 gr; D = 5,76× 10^{-2} cm^2/h. Other data on statistical parameters are given in Table 2.

The target level of reliability of CPS components is taken as P_{targ} = 0,9 (β = 1,28). Due to short service time of steel reinforcement in acid environment, the initiation of reinforcement corrosion is accepted as SLS. Therefore, the third term in Eq (5) or (7) disappears. For simplicity we assume that υ_t = 1,0. The design service time of reinforced concrete storage structure t_d = 30 years.

Table 2. Statistical parameters of random variables

Parameter*	Mean	COV	
Concrete cover, d_c mm	22,2	0,15	determined
Polymer coating, d_b mm	1,0	0,12	determined
Rate of degradation,			
λ_c cm/h$^{1/2}$	0,0048	0	computed
λ_b 1/year	0,131	0	determined
Time to failure		0,3	assumed
Model errors, θ_d	1,0	0,1	assumed
θ_x	1,0	0,15	assumed

*all parameters are assumed as normal distributed.

1. Concrete cover degradation depth

It is assumed that deterioration will lead to a uniform reduction in the thickness of cover. Substituting in Eq (15) the relevant values for concrete cover ($d_{bm} = d_{cm}$; $x_{bm}(t) = x_{cm}(t)$), the following equation is obtained

$$P\{t_c\} = \Phi\left\{\frac{22{,}2 - x_{cm}(t)}{22{,}2^2(0{,}15^2 + 0{,}1^2) + x_{cm}{}^2(t)(0{,}38^2 + 0{,}15^2)}\right\} = \Phi(1{,}28).$$

Solving this expression, we can find the unknown mean value of deterioration depth $x_{cm}(t) = 15{,}15$ mm.

2. Service life of concrete cover

Degradation of concrete cover can be expressed using Eq (16), where n = 2 and

$$\lambda_c = \sqrt{2Dc_0 / Ck_{CaO}} = \sqrt{2 \times 0{,}00576 \times 0{,}049 / 400 \times 0{,}62} = 0{,}0048\, cm / h^{1/2}.$$

Substitution of previously obtained value of $x_{cm}(t)$ and computed value of λ_c into Eq (16) gives the mean time t_{cm} = 11,4 years. Then

$$t_c = t_{cm}(1 - \beta_t V_t) = 11{,}4(1 - 1{,}28 \times 0{,}3) \cong 7 \text{ years} < t_d.$$

The structure needs additional protection coating against acid attack.

3. Design of protection coating

It is suggested to use a three-layer coat based on IKA resin. The mean thickness of coating is 1,0 mm, V_d = 0,12. The reliability of coating can be verified using a similar procedure as for concrete cover.

$$P\{t_b\} = = \Phi\left\{\frac{1 - x_{bm}(t)}{1^2(0{,}12^2 + 0{,}1^2) + x_{bm}{}^2(t)(0{,}3^2 + 0{,}15^2)}\right\} = \Phi(1{,}28)$$

from which the mean deterioration depth of coating $x_{bm}(t) \cong 0{,}61$ mm.

Eq (14) gives deterioration depth of coating in acid water, where $a = 1 + \lambda_b t$. Then deterioration mean depth is

$$0{,}61 = 1{,}0[1 - (1 + 0{,}131 \times t)\exp(-0{,}131 \times t)],$$

from which the mean service time of coating $t_{bm} = 15{,}7$ years.

The service time of coating is expressed as

$$t_b = t_{bm} - \beta_t V_t (t_{bm} - t_{cm}) = 15{,}7 - 1{,}28 \times 0{,}3(15{,}7 - 11{,}4) \cong 14$$

years.

When $t_b + t_c = 14 + 7 = 21 < t_d$, the recoating at the age of 14 years should be done. Assuming that the recoating time is negligible, further coating deterioration and failure at 28 years is expected.

4. Service life of CPS

Mean service life of CPS is calculated as

$$T_{CPS} = 2 \times t_{bm} + t_{cm} = 2 \times 15{,}7 + 11{,}4 = 42{,}8 \text{ years},$$

and reliability of protection system is

$$P_{CPS}\{T_{CPS} \geq t_d\} = (2 \times 14 + 7) = 35 > t_d = 30 \text{ years.}$$

7. Conclusions

Based on this study, the following conclusions can be drawn:

1. Deterioration of reinforced concrete structures exposed in man-made or atmospheric aggressive conditions is a common problem in many countries of the world. Frequently, due to corrosion, the resistance of structures decreases much earlier than their expected service life. One of the ways to protect reinforced concrete structures from corrosion is to use protective coatings. In current practice, the use of coatings is based on the standard recommendations in the proper choice of the correct type of the coating material for the particular application. A simplified and unified design procedures based on the mechanism of degradation for the full range of reinforced concrete structures exposed in various aggressive conditions is a more rational way. Design of durability of concrete structures with protective coatings needs to be established.

2. A model of deterioration and service life prediction of corrosion protection multi-level system, which is represented by protective surface barrier, concrete cover, and steel reinforcement itself, of reinforced concrete structures was developed [Eqs (6), (7), (8) and (9), Fig. 3]. The model relates the entire service life of corrosion protection system to the rate of degradation of its components. Reliability based assessment of protection system taking into account its components degradation is indispensable [Eqs (10), (11), (12), (13)]. Variables in the model are uncertain and must be described using probability distributions.

3. The model developed may be applied to a variety of new or existing structures in order to predict the time to first repair/rehabilitation of reinforced concrete structures and to develop reliability-based corrosion protection systems. Although the practical use of this model requires further study. Degradation models and their characteristics, including failure rates, λ_i, must be identified for a particular structures (transportation structures, marine structures, chemical storage tanks, pipes, sewers, and other facilities) and exposure conditions. It is believed, when these studies are conducted the variables to be investigated will be consistent with the proposed concept of multi-layer protection system and will provide more realistic service-life predictions and adequate basis for anticorrosion protection design. Since protection measures are costly decisions, final protection system should be taken into analysis and economic considerations.

References

Allam, I. M.; Maslchuddin, M.; Saricimen, H.; Al-Mana, A. I. 1994. Influence of atmospheric corrosion on mechanical properties of reinforcing steel, *Construction and Building Materials* 8(1): 35–41.

Almusallam, A. A. 2001. Effect of degree of corrosion on the properties of reinforcing steel bars, *Construction and Building Materials* 15(8): 361–368.

Almusallam, A.; Khan, F. M.; Maslehuddin, M. 2002. Performance of concrete coatings under varying exposure conditions, *Materials and Structures* 35(8): 487–494.

Almusallam, A.; Khan, F. M.; Dulaidjan, S. U.; Al-Amoudi, O. S. B. 2003. Effectiveness of surface coatings in improving concrete durability, *Cement and Concrete Composites* 25(4–5): 473–481.

Amey, S. L.; Johnson, D. A.; Miltenberger, M. A.; Farzam, H. 1998. Predicting the service life of concrete marine structures, *ACI Material Journal* 95(2): 205–214.

Andrade, C.; Alonso, C.; Molina, F. J. 1993. Cover cracking as a function of rebar corrosion: part I – experimental test, *Materials and Structures* 26(8): 453–464.

Bentz, E. C. 2003. Probabilistic modeling of service life for structures subjected to chlorides, *ACI Materials Journal* 100(5): 391–397.

Chung, D. D. L. 2004. Use of polymers for cement-based structural materials, *Journal of Material Science* 39(9): 2973–2978.

Coronelli, D. 2002. Corrosion cracking and bond strength modeling for corroded bars in reinforced concrete, *ACI Structural Journal* 99(3): 267–276.

Delicchi, M.; Barbucci, A.; Cerisola, G. 2004. Crack-bridging ability of organic coatings for concrete: influence of the method of concrete cracking, thickness and nature of the coating, *Progress in Organic Coatings* 49(4): 336–341.

DuraCrete/BE95-1347/R4-5. 1998. *Modeling of Degradation.* Task 2 Report. UK. 174 p.

Gonzales, J. A.; Feliu, S.; Rodriguez, P.; Lopez, W.; Alonso, C.; Andrade, C. 1996. Some questions on the corrosion of steel in concrete II: corrosion mechanism and monitoring, service life prediction and protection methods, *Materials and Structures* 29(2): 97–104.

Jokubaitis, V. 2007. Regularities in propagation of opened corrosion-induced cracks in concrete, *Journal of Civil Engineering and Management* 13(2): 107–113.

Kamaitis, Z. 2002. Damage to concrete bridges due to reinforcement corrosion. Part I – Site investigations, *Transport* 17(4): 137–142.

Kamaitis, Z. 2007a. Structural design of protective polymer coatings for reinforced concrete structures. Part I: General design consideration, *Journal of Civil Engineering and Management* 13(1): 11–17.

Kamaitis, Z. 2007b. Structural design of protective polymer coatings for reinforced concrete structures. Part II: Experimental verification, *Journal of Civil Engineering and Management* 13(1): 19–26.

Mays, G. C. 1999. Materials for protection and repair of concrete: progress towards European standardization, in *Proc of the International Conference – Concrete Durability and Repair Technology*. Ed. by Dhir, R. K.; McCarthy, M. J. 8–10 September, 1999, Dundee, Scotland (UK). Thomas Telford, 481–491. ISBN 0 7277 2826 1.

Maruyama, K. 1999. Life-cycle behaviour of reinforced concrete structures – what do we need to know? in *Proc of IABSE Symposium – Structures for the Future-The Search for Quality.* August 25–27, 1999, Rio de Janeiro (Brazil). IABSE 8(1), 33–41. ISBN 3-85748-100-6.

McCarthy, M. J.; Giannakou, A.; Jones, M. R. 2004. Comparative performance of chloride attenuating and corrosion inhibiting systems for reinforced concrete, *Materials and Structures* 37(10): 671–679.

Medeiros, M.; Helene, P. 2008. Efficacy of surface hydrophobic agents in reducing water and chloride ion penetration in concrete, *Materials and Structures* 41(1): 59–71.

Raupach, M.; Wolff, L. 2005. Long-term durability of hydrophobic treatment on concrete, *Surface Coatings International Part B: Coatings Transactions* 88(2): 127–133.

Remmele, T. E. 2003. Specifying high-performance coatings for concrete, *Construction Specifier* 56(9): 49–54.

Rodrigues, M. P. M.; Costa, M. R. N.; Mendes, A. M.; Marques, M. I. 2000. Effectiveness of surface coatings to protect reinforced concrete in marine environments, *Materials and Structures* 33(10): 618–626.

Schiessl, P. 1994. Draft recommendation for repair strategies for concrete structures damaged by reinforcement corrosion, *Materials and Structures* 27(7): 415–436.

Seneviratne, A. M. G.; Sergi, G.; Page, C. L. 2000. Performance characteristics of surface coatings applied to concrete for control of reinforcement corrosion, *Construction and Building Materials* 14(1): 55–59.

Val, D. V.; Stewart, M. G. 2003. Life-cycle cost analysis of reinforced concrete structures in marine environments, *Structural Safety* 25(4): 343–362.

Vipulanandan, C.; Liu, J. 2005. Performance of polyurethane-coated concrete in sewer environment, *Cement and Concrete Research* 35(9): 1754–1763.

Камайтис, З. 1992. Восстановление и усиление конструкций и сооружений синтетическими смолами [Kamaitis, Z. Repair and strengthening of structures and buildings by synthetic resins]. Вильнюс: Техника. 280 с.

GELŽBETONINIŲ KONSTRUKCIJŲ SU PAVIRŠINĖMIS DANGOMIS KOROZINĖS APSAUGOS MODELIAVIMAS

Z. Kamaitis

Santrauka

Korozija yra svarbi gelžbetoninių konstrukcijų ilgaamžiškumo problema. Gelžbetonines konstrukcijas būtina apsaugoti nuo korozijos įvairiomis sąlygomis, pradedant nuo atmosferos iki nuolatinio mirkymo vandenyje ar chemikaluose. Vienas iš apsaugos būdų yra polimerinės apsauginės dangos. Atsparus paviršinis barjeras gali labai sulėtinti gelžbetonio irimą ir išspręsti daugelį problemų, susijusių su išorine aplinka. Reikia sukurti gelžbetoninių konstrukcijų su apsauginėmis dangomis projektavimo metodiką. Straipsnyje nagrinėjama antikorozinės apsauginės sistemos, susidedančios iš paviršiaus apsauginio barjero, apsauginio betoninio sluoksnio ir pačios plieninės armatūros, patikimumas ir spėjamas gyvavimo laikotarpis. Šis modelis remiasi apsauginio barjero, betonio sluoksnio ir armatūros irimo procesų samprata. Skaitinis pavyzdys rodo antikorozinės apsauginės sistemos patikimumo patikrą.

Reikšminiai žodžiai: gelžbetonis, korozija, antikorozinė apsauga, patikimumas, laikas iki suirties.

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